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TRANSPORT OF NON–SYMMETRIC ION BEAMS IN ROTATING ION–OPTICAL SYSTEMS

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Transport of ion beams in rotating ion-optical systems is discussed in the paper. Special attention is paid to the transport of beams with different emittances in the horizontal and vertical plane (non-symmetric beams). Summary of theoretical matrix analysis of the problem is presented. Different matching methods are reviewed and compared. A novel solution that has recently been granted a US-Patent is presented. An example is given for transport of ion-therapy beams through an isocentric rotating gantry. Theoretical considerations and results are, however, valid for other types of rotating systems, as well.

K e y w o r d s: beam-transport, emittance, gantry, ion optics, ion therapy

1 INTRODUCTION

In some special applications, for example in ion-therapy accelerator complexes, the beams are transported through rotating ion-optical systems. A part of the beam-line is mechanically rotated with respect to the rest of the accelerator complex. Ion-optical design of a system containing rotating parts becomes complicated, if the beam has different emittances in the transverse planes (non-symmetric beam). The asymmetry between the transverse emittances may be caused for example by resonant slow extraction from a synchrotron [1] or by any other asymmetrical conditions during the beam acceleration and transport upstream the rotating system. In such a case, the beam parameters at the entrance to the rotating system become a function of the rotation angle and this angular dependence is, in general, transferred to the whole subsequent beam-transport system. There are few papers dealing with this problem [2–8], each of them presenting a solution under some particular circumstances. Several design strategies can be recognized. In this paper, different solutions are reviewed and compared. Special attention is paid to a novel solution of a rotating ion-therapy gantry that has been chosen for the clinical accelerator facility in Heidelberg [9].

1.1 Possible design strategies

Possible design strategies can be classified into three categories:

- the input beam parameters are "rotated" together with the mechanical rotation of the system;
- the ion-optical setting of the rotating beam-line is a function of the rotation angle;
- the ion-optical setting of the rotating beam-line is not a function of the rotation angle, but fulfills special ion-optical constraints.

In order to discuss and to compare those possible design strategies, theoretical background is summarized. It is based on the beam-transport matrix formalism as known from particle accelerator physics [10].

2 THEORETICAL BACKGROUND

2. 1 Matrix formalism

In particle accelerator physics, the beam-transport is usually described with the aid of the transfer matrix and the sigma-matrix. The transfer matrix $\mathbf{M}$ describes the action of an ion-optical element on individual particle trajectories and is defined as:

$$\mathbf{X}_{out} = \mathbf{M}\mathbf{X}_{in} \tag{1}$$

where $\mathbf{X}_{out}$ and $\mathbf{X}_{in}$ are vectors containing the particle co-ordinates at the exit and at the entrance of the ion-optical element, respectively. The particle co-ordinate vector contains six co-ordinates:

$$\mathbf{X} = \begin{pmatrix} x & x' & z & z' & \Delta l & \frac{\Delta p}{p_0} \end{pmatrix}^\top \tag{2}$$

where x, x', z and z' are particle position and angle with respect to the reference trajectory in horizontal and vertical plane, Δl is the path-length difference between the particle trajectory and the reference trajectory and $\frac{\Delta p}{p_0}$ is the relative momentum deviation of the particle from the reference one. The path-length difference Δl is irrelevant for transverse beam-optics and will be ignored in the present study.

A sequence of n ion-optical elements with individual transfer matrices $\mathbf{M}_1, \mathbf{M}_2, \dots, \mathbf{M}_n$ will have an overall transfer matrix $\mathbf{M}_{over} = \mathbf{M}_n\mathbf{M}_{n-1}\cdots\mathbf{M}_2\mathbf{M}_1$. If the particle energy is constant, determinant of any transfer matrix equals one.

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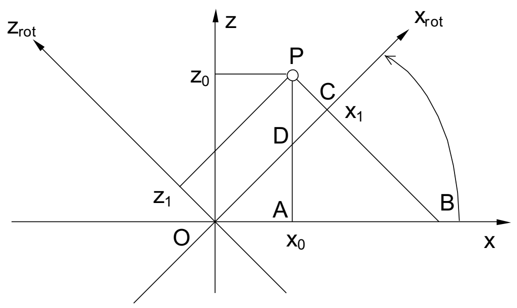

Fig. 1. Transformation of the particle co-ordinates due to the co-ordinate system rotation.

The sigma-matrix of the beam $\boldsymbol{\sigma}$ is defined by the equation of an ellipsoid describing the phase-space volume of the beam:

$$\mathbf{X}^\top \boldsymbol{\sigma}^{-1} \mathbf{X} = 1 \tag{3}$$

The action of an ion-optical element on the sigma-matrix is given [10]:

$$\boldsymbol{\sigma}_{out} = \mathbf{M} \boldsymbol{\sigma}_{in} \mathbf{M}^\top \tag{4}$$

where $\boldsymbol{\sigma}_{in}$ and $\boldsymbol{\sigma}_{out}$ are the sigma-matrices of the beam at the entrance and at the exit of the ion-optical element, respectively.

2.2 Co-ordinate system rotation transfer matrix

Let us assume an ion-optical system that is mechanically rotated with respect to the fixed incoming beam-line by an angle β (positive for anticlockwise rotation). *The fixed co-ordinate system* $[\,x \quad z\,]$ is attached to the incoming beam-line, whereas *the rotated co-ordinate system* $[\,x_{rot} \quad z_{rot}\,]$ is attached to the rotating ion-optical system. Let us transform the particle co-ordinates $[\,x_0 \quad z_0\,]$ in the fixed co-ordinate system to particle co-ordinates $[\,x_1 \quad z_1\,]$ in the rotated co-ordinate system. The situation is illustrated in Fig. 1.

The angle of rotation β appears also at the vertex "P" of the triangle "PAB", giving the distance $|AB| = z_0 \tan\beta$. The co-ordinate x_1 can be calculated from the triangle "OCB":

$$\begin{aligned} x_1 = \big(x_0 + |AB|\big)\cos\beta &= x_0\cos\beta + z_0\tan\beta\cos\beta \\ &= x_0\cos\beta + z_0\sin\beta\,. \end{aligned} \tag{5}$$

Because the angle of rotation β is not a function of the beam-path, derivation of (5) yields:

$$x_1' = x_0'\cos\beta + z_0'\sin\beta \tag{6}$$

Similarly, the co-ordinate z_1 can be obtained using the distance $|AD| = x_0\tan\beta$:

$$|PD| = z_0 - |AD| = z_0 - x_0\tan\beta\,. \tag{7}$$

The new co-ordinate z_1 can be calculated from the triangle "PDC":

$$\begin{aligned} z_1 = |PD|\cos\beta &= (z_0 - x_0\tan\beta)\cos\beta \\ &= -x_0\sin\beta + z_0\cos\beta \end{aligned} \tag{8}$$

Derivation of (8) yields:

$$z_1' = -x_0'\sin\beta + z_0'\cos\beta \tag{9}$$

Momentum spread is not affected by the co-ordinate system rotation. In the matrix notation, equations (5), (6), (8), (9) can be written as:

$$\begin{aligned} \begin{pmatrix} x_1 \\ x_1' \\ z_1 \\ z_1' \\ \frac{\Delta p}{p_0} \end{pmatrix} &= \begin{pmatrix} \cos\beta & 0 & \sin\beta & 0 & 0 \\ 0 & \cos\beta & 0 & \sin\beta & 0 \\ -\sin\beta & 0 & \cos\beta & 0 & 0 \\ 0 & -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ z_0 \\ z_0' \\ \frac{\Delta p}{p_0} \end{pmatrix} \\ &= \mathbf{M}(\beta) \begin{pmatrix} x_0 & x_0' & z_0 & z_0' & \frac{\Delta p}{p_0} \end{pmatrix}^\top \end{aligned} \tag{10}$$

where $\mathbf{M}(\beta)$ is the transfer matrix describing the co-ordinate system rotation by an angle β. Obviously, rotation of the co-ordinate system causes coupling between the horizontal and vertical transverse planes.

3 METHODS OF TRANSPORTING NON–SYMMETRIC BEAMS

3.1 Rotator concept

The rotator concept is based on inserting a dedicated matching section called "rotator" inbetween the fixed beam-line and the rotating ion-optical system. Let the transfer matrix of the rotator $\mathbf{M}_{rot}$ be:

$$\mathbf{M}_{rot} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \tag{11}$$

If the ion-optical system is rotated by an angle β with respect to the fixed beam-line, the rotator must be rotated by the angle $\frac{\beta}{2}$. This means, that the angle $\frac{\beta}{2}$ appears between the exit of the fixed beam-line and the entrance to the rotator and another angle $\frac{\beta}{2}$ appears between the exit of the rotator and the entrance to the rotating ion-optical system. The overall transfer matrix from the exit of the fixed beam-line to the entrance of the rotating system $\mathbf{M}_{over}$ will be:

$$\mathbf{M}_{over} = \mathbf{M}\Big(\frac{\beta}{2}\Big)\mathbf{M}_{rot}\mathbf{M}\Big(\frac{\beta}{2}\Big). \tag{12}$$

For the rotator matrix according to (11), the matrix multiplication yields $\mathbf{M}_{over} = \mathbf{M}_{rot}$, which is the unit matrix in the horizontal plane and the "minus-unit" matrix in the vertical plane. This means, that in the horizontal plane, particles will enter the rotating beam-line with exactly the same co-ordinates (expressed in the rotated co-ordinate system) as they left the fixed part (the fixed co-ordinate system). In the vertical plane, their co-ordinates will be reversed. Assuming a beam containing always both $[\,z_0 \quad z_0'\,]$ as well as $[\,-z_0 \quad -z_0'\,]$ particles, this effect does not play any role. The $[\,z_0 \quad z_0'\,]$ and $[\,-z_0 \quad -z_0'\,]$ particles just exchange their positions in the emittance diagram. The beam parameters in the rotated co-ordinate system are therefore identical to the beam parameters in the fixed co-ordinate system in both planes. In other words, they are rotated together with the co-ordinate system rotation.

It can be shown that the rotator principle works for any matrix like:

$$\mathbf{M}_{rot} = \begin{pmatrix} r & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{r} & 0 & 0 & 0 \\ 0 & 0 & -r & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{r} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \tag{13}$$

The latest result (13) represents a matching section that combines rotation of the co-ordinate system with the beam-size control. Such a rotator has not been considered in the published works yet. The matrix (11) is a special case of the matrix (13) for $r = 1$.

3.2 Non-rotator concepts

Without using the rotator, the beam parameters at the entrance to the rotating ion-optical system become a function of the rotation angle. This angular dependence is, in general, transferred to the whole subsequent beam-line. It would be possible to compensate for this by using different ion-optical settings for different angles. In fact, each angle represents a different beam-line that would have to be designed individually. It is an issue whether a suitable setting exists for each angle because of physical limits of individual beam-transport elements. Some systems, for example a set of dipole magnets, do not offer enough ion-optical flexibility, i.e. there is a lack of variable elements that could be adjusted as a function of the rotation angle. However, even if this were possible, a large data set would have to be calculated, stored and managed, which increases the probability of errors and incorrect beam parameters and reduces the reliability, safety and operational comfort. That is why, this approach has never been seriously considered as a real option.

Angular independence of some beam-parameters can also be achieved by applying a special set of ion-optical constraints upon the rotating part of the beam-line. Let us assume that the beam is described at the exit of the fixed beam-line and at the exit of the rotating system by sigma-matrices $\boldsymbol{\sigma}(0)$ and $\boldsymbol{\sigma}(1)$, respectively. Let the rotating ion-optical system be characterized by its transfer matrix $\mathbf{M}$. If the system is rotated with respect to the fixed beam-line by an angle β, the sigma-matrix of the beam at the exit of the rotating ion-optical system, $\boldsymbol{\sigma}(1)$, will be:

$$\boldsymbol{\sigma}(1) = \mathbf{MM}(\beta)\boldsymbol{\sigma}(0)\,[\mathbf{MM}(\beta)]^{\top}\,. \tag{14}$$

Matrix multiplication (14) could now be used to evaluate and analyze all individual terms of the sigma-matrix at the exit of the rotating ion-optical system from the point of view of their dependency on the rotation angle. In order to simplify this analysis, some physically justified simplifications are introduced at this point.

The incoming fixed beam-line is expected to be a double-achromatic ion-optical system with no coupling between horizontal and vertical plane. The sigma-matrix of the beam at the exit of the fixed beam-line will therefore look like:

$$\boldsymbol{\sigma}(0) = \begin{pmatrix} \sigma(0)_{11} & \sigma(0)_{12} & 0 & 0 & 0 \\ \sigma(0)_{12} & \sigma(0)_{22} & 0 & 0 & 0 \\ 0 & 0 & \sigma(0)_{33} & \sigma(0)_{34} & 0 \\ 0 & 0 & \sigma(0)_{34} & \sigma(0)_{44} & 0 \\ 0 & 0 & 0 & 0 & \sigma(0)_{55} \end{pmatrix}. \tag{15}$$

Furthermore, there is no coupling in the rotating ion-optical system itself, which means:

$$\mathbf{M} = \begin{pmatrix} r_{11} & r_{12} & 0 & 0 & r_{15} \\ r_{21} & r_{22} & 0 & 0 & r_{25} \\ 0 & 0 & r_{33} & r_{34} & r_{35} \\ 0 & 0 & r_{43} & r_{44} & r_{45} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \tag{16}$$

Let us restrict the study on the size and shape of the beam-spot, which are the most important beam-parameters for majority of the common ion-beam applications. A circular beam-spot (round beam) and the beam-size independent from the angle of rotation correspond to the constraints:

$$\sigma(1)_{11} = \sigma(1)_{33} \neq f(\beta) \text{ and } \sigma(1)_{13} = 0 \neq f(\beta)\,. \tag{17}$$

The pertinent terms can be calculated using transformation (14). The $\sigma(1)_{11}$ term describing the beam-size in the horizontal plane at the exit of the rotating system is obtained as:

$$\begin{aligned} \sigma(1)_{11} = {} & r_{11}^2 \left\{\sigma(0)_{11}\cos^2\beta + \sigma(0)_{33}\sin^2\beta\right\} \\ & + r_{12}^2 \left\{\sigma(0)_{22}\cos^2\beta + \sigma(0)_{44}\sin^2\beta\right\} \\ & + 2r_{11}r_{12}\left\{\sigma(0)_{12}\cos^2\beta + \sigma(0)_{34}\sin^2\beta\right\} \\ & + r_{15}^2\sigma(0)_{55}\,. \end{aligned} \tag{18}$$

Eliminating the β-containing terms is feasible. If $r_{11} = 0$ and $\sigma(0)_{22} = \sigma(0)_{44}$, the beam size in the horizontal plane will be independent from the rotation angle. The condition $r_{11} = 0$ is a constraint that must be fulfilled by the rotating ion-optical system, whereas satisfying the constraint $\sigma(0)_{22} = \sigma(0)_{44}$ is a job for the incoming fixed beam-line. In other words, the incoming beam-line must

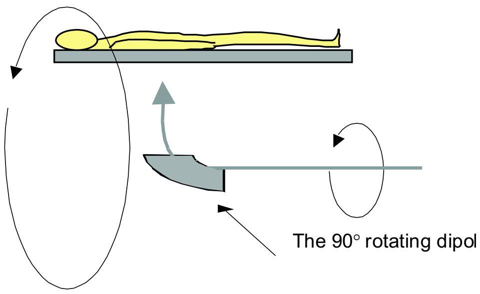

Fig. 2. Principal scheme of the magnet-isocentric "Riesenrad" gantry. Showed is the 90 ° rotating dipole and the patient moved around the dipole.

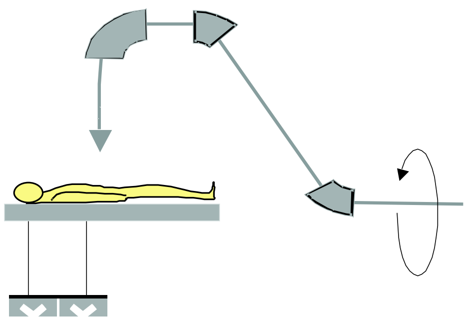

Fig. 3. Principal scheme of the patient-isocentric rotating gantry. Showed are bending magnets of the gantry and the fixed patient couch.

"prepare" the beam to satisfy the $\sigma(0)_{22} = \sigma(0)_{44}$ constraint and the rotating ion-optical system must perform parallel-to-point imaging. Another possibility is to satisfy $r_{12} = 0$ and $\sigma(0)_{11} = \sigma(0)_{33}$. This corresponds to point-to-point imaging. Identical set of constraints can be obtained in the vertical plane by evaluating the $\sigma(1)_{33}$ term:

$$\begin{aligned} &\{r_{33} = 0 \text{ and } \sigma(0)_{22} = \sigma(0)_{44}\} \\ \text{or } &\{r_{34} = 0 \text{ and } \sigma(0)_{11} = \sigma(0)_{33}\}. \end{aligned} \tag{19}$$

The xz-correlation term $\sigma(1)_{13}$ will be:

$$\begin{aligned} \sigma(1)_{13} &= \sin\beta\cos\beta\big\{r_{11}r_{33}(\sigma(0)_{33} - \sigma(0)_{11}) \\ &+ r_{11}r_{34}(\sigma(0)_{34} - \sigma(0)_{12})\big\} + \sin\beta\cos\beta\big\{r_{12}r_{34}(\sigma(0)_{44} \\ &- \sigma(0)_{22}) + r_{12}r_{33}(\sigma(0)_{34} - \sigma(0)_{12})\big\} + r_{15}r_{35}\sigma_{55} \end{aligned} \tag{20}$$

The xz-correlation term will be zero and independent from the rotation angle, if the rotating ion-optical system will be achromatic at least in one transverse plane ($r_{15} = 0$ or $r_{35} = 0$) and the following set of constraints will be satisfied:

$$\begin{aligned} &\{r_{11} = r_{33} = 0 \text{ and } \sigma(0)_{22} = \sigma(0)_{44}\} \\ \text{or } &\{r_{12} = r_{34} = 0 \text{ and } \sigma(0)_{11} = \sigma(0)_{33}\} \end{aligned} \tag{21}$$

This set is, however, consistent with the constraints for rotation independent beam size in the horizontal and vertical plane simultaneously. It means, that rotation independent beam-spot without xz-correlation is feasible to achieve. Round beam, *ie* $\sigma(1)_{11} = \sigma(1)_{33}$ must be achieved by a proper control of remaining non-zero terms of the transfer matrix. Although this is theoretically possible, it is a challenge to satisfy all the above ion-optical constraints in a real beam-transport system. The first design of this type worldwide is presented in the next section.

4 APPLICATION OF THE RESULTS TO ION–THERAPY GANTRIES

Gantry is a terminating part of the beam-line transporting the beam from the accelerator to the patient. It is mechanically rotated around the incoming beam axis in order to irradiate the patient from any angle that is determined by a physician. Historically, first gantry designs assumed symmetric beams only [11, 12]. This assumption is close to reality for the beams produced by cyclotrons in proton therapy [13], but became an issue after the Proton/Ion Medical Machine Study (PIMMS) [14]. The PIMMS-Study showed that the synchrotron gantries should be able to transport the non-symmetric beams. The study also introduced the rotator concept in combination with a so-called "Riesenrad" gantry. The Riesenrad gantry (Fig. 2) is a magnet-isocentric structure, consisting of a single rotating 90 ° dipole and an upstream quadrupole matching section. The patient must be moved around the dipole with the aid of a special mechanical structure in order to follow the dipole rotation [15]. From the beam-transport point of view, the ion-optical flexibility is very limited. The main problem is to match the dispersion of the 90 ° dipole. Double achromatic beam-transport can never be achieved in the structure containing only a single dipole magnet. Using the rotator is necessary in this case. However, the rotator occupies about 10–15 meters in the transfer line, which may not fit to the limited space of a hospital. That was why the non-rotator concept has been developed. Ion-optical properties of the rotator are thoroughly described and discussed in [3, 5].

The novel non-rotator concept has been applied to a patient-isocentric gantry (Fig. 3). The gantry consists of three bending magnets and certain number of quadrupoles. It is rotated around the fixed patient. Because the patient is not moved, the isocentric gantry is strongly preferred by medical community. From the beam-transport point of view, the presence of several dipoles and quadrupoles enables to fit ion-optical constraints derived in Section 3.2.

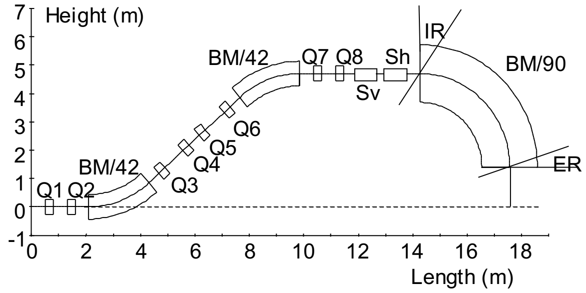

Fig. 4. Layout of the isocentric gantry: Q1–Q8 are quadrupoles, BM/42 — 42° bending magnet, BM/90 — 90° bending magnet, Sh — horizontal scanner, Sv — vertical scanner, IR — input pole face rotation (30°), ER — exit pole face rotation (21°).

4.1 Computer simulations of the beam transport in the isocentric gantry

Results based on the matrix analysis must be interpreted with a great care. Fitting the overall transfer matrix constraints gives no guarantee on realistic beam-transport conditions inside the system. Analytical results based on the matrix formalism must therefore be followed by computer simulations. Final gantry design includes also design of all individual magnets [16] and the mechanical supporting structure. Ion-optical design must respect many additional constraints and becomes a complex task. The goal for computer simulations is to fit the overall transfer matrix constraints with realistic physical and electrical parameters of the magnets, with reasonable beam-envelopes (aperture) and under feasible conditions for gantry assembling. In our case, the maximum allowable magnetic field was 2 T for dipoles and 0.7 T for quadrupoles on the pole-tips. Minimum drift space between any two adjacent magnets was 0.5 m. A scanning system was placed upstream the last dipole in order to provide parallel beam-scanning [7, 11, 12] at the patient position.

The input beam parameters were 3 mm · 0.333 mrad horizontally, 15 mm · 0.333 mrad vertically, waists, momentum spread 0.2 % [7]. The input beam parameters correspond to the emmitance ratio $\varepsilon_{\text{vert}}/\varepsilon_{\text{hor}} = 5$. The maximum magnetic beam rigidity was 6.6 Tm, which corresponds to 430 MeV/u carbon ion beam with the penetration range of 30 cm in water.

The ion-optical study was performed with the aid of the TRANSPORT-code. The resulting gantry layout is shown in Fig. 4. The study showed that it was not possible to fit the point-to-point imaging, but it was possible to achieve the parallel-to-point imaging. Parallel-to-point imaging was even possible for adjustable output beam-size from 4 to 10 mm (beam-diameter). The gantry is double achromatic.

Figures 5 and 6 illustrate the rotation independence of the beam-spot for 4 mm and 10 mm output beam, respectively. The beam envelopes are shown for rotation angles from 0° to 90° in 10° steps. In one extreme position (0°), the horizontal plane of the gantry transports the beam with the minimum emittance (minimum input beam-diameter) while the vertical plane of the gantry transports the beam with the maximum emittance (maximum input beam-diameter). In the second extreme position (90°), the situation is inversed. Other beam-envelopes showed correspond to the rotation angles from 10° to 80° . The output beam-diameter is independent from the angle of gantry rotation and can be adjusted from 4 mm to 10 mm.

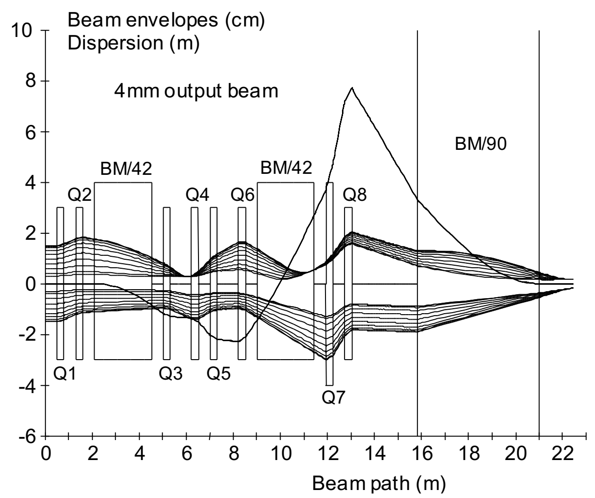

Fig. 5. Beam envelopes in the gantry for 4mm output beam-diameter. The beam envelopes are given for the gantry angles from 0° to 90°, 10° steps. Q1–Q8 are quadrupoles, BM/42 — 42° bending magnet, BM/90 — 90° bending magnet, upper plot — horizontal plane of the gantry, lower plot — vertical plane of the gantry, dashed line — dispersion function.

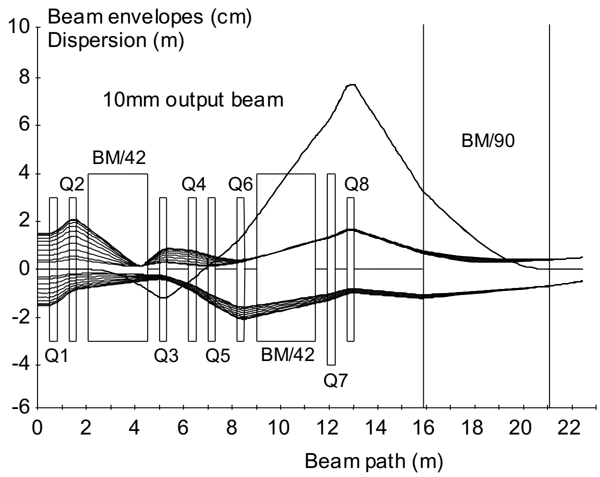

Fig. 6. Beam envelopes in the gantry for 10 mm output beam-diameter. The beam envelopes are given for the gantry angles from 0° to 90°, 10° steps. Q1—Q8 are quadrupoles, BM/42 — 42° bending magnet, BM/90 — 90° bending magnet, upper plot — horizontal plane of the gantry, lower plot — vertical plane of the gantry, dashed line — dispersion function.

The presented gantry is an original and unique beam-transport system that has recently been granted a US-Patent [17].

4.2 Experimental verification

No rotating heavy-ion gantry has been constructed so far. That is why, it has not been possible to verify the proposed beam-transport system yet except for running independent computer simulations by two different codes, TRANSPORT [18] and WinAGILE [19]. The computer simulations showed an excellent agreement.

The main problem of the gantry construction is a mechanical supporting structure capable of carrying and rotating the gantry with a desirable accuracy. Submillimeter beam-position accuracy at the patient is usually required. Prototyping and testing of the terminating part of the gantry (scanning system with the large-aperture 90° dipole) is currently in progress at GSI Darmstadt [20].

5 COMPARISON STUDY AND DISCUSSION

5.1 Protons versus heavy-ions

Heavy-ions require different beam-delivery techniques compared to protons. Proton therapy beams are usually formed by passive beam-delivery systems (scattering and collimation) whereas heavy-ions should preferably be delivered by pencil-beam scanning [21]. That is why, the problem of non-symmetric beam-transport is less relevant for protons even if they are produced by a synchrotron. It is also not relevant for cyclotrons because the extraction techniques used in cyclotrons are different from those used in synchrotrons. The proton gantries are therefore designed and operated successfully assuming the symmetric ion-optical properties of the beam [13]. It is the combination of the resonant slow-extraction with the pencil-beam scanning and the rotating gantry, which requires the special beam-transport precautions as described in this paper.

5.2 Rotator versus non-rotator concept

There are essential differences between the rotator and the non-rotator concepts. As far as the principle is concerned, the rotator removes the angular dependence of the beam parameters at the entrance to the rotating system. This is achieved by an extra matching section with a special transfer matrix that maps particle co-ordinates from the fixed co-ordinate system into the rotated co-ordinate system. This is equally true for particles displaced due to the dispersion of the incoming beam-line. That is why, the rotator is able to match even non-achromatic rotating systems like the Riesenrad gantry [15]. The rotator concept is a universal approach that can be applied to any rotating ion-optical system and provides full rotation independence of all beam parameters. A disadvantage is an extra space needed for the rotator (10–15 m of the beam-line) and mechanical rotation of two beam-transport subsystems, the rotator and the gantry. The first may cause problems to fit the limited space available at a hospital, the latest may contribute to the beam-position inaccuracy due to the mechanical misalignments of the rotated beam-transport elements.

Two types of the rotator transfer matrix have been studied in the literature. A generalized form of the rotator transfer matrix (13) has been introduced in this paper. The non-rotator concept removes the angular dependence of some beam parameters at the exit of the rotating system still tolerating the angular dependence of the input beam parameters. It can be applied to achromatic systems only that are, in addition, able to fit a special set of ion-optical constraints. The angular dependence can only be achieved for selected output beam parameters. A disadvantage of the non-rotator concept is therefore obviously the restricted applicability. An advantage is, that matching is in fact done by the gantry beam-transport system itself without any additional space needed for a matching section.

There are two different sets of ion-optical constraints based on either parallel-to-point or point-to-point imaging. The only successful design so far has been achieved for parallel-to-point imaging [17]. Special imaging conditions may be exploited for making the beam-transport less sensitive to mechanical misalignments, which may simplify the design of the mechanical supporting structure. For example, the parallel-to-point gantry will entirely be insensitive to shifting the whole structure with respect to the incoming beam-line supposing that the gantry aperture is designed with a reasonable safety margin. Working on these beam-transport aspects is currently in progress.

6 CONCLUSIONS

It has been demonstrated that there are several different ways possible to transport non-symmetric beams through rotating ion-optical systems. They are systematically described and compared in the paper from the point of view of working principle as well as applicability.

Their advantages and restrictions have been discussed. Theoretical considerations have been applied to ion-therapy gantries. A patented isocentric gantry based on the non-rotator concept has been presented. This gantry is going to be built and installed at the dedicated ion-therapy accelerator complex in Heidelberg, Germany.

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